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The goals of this research were to develop a GIS workstation to examine the distribution, relative abundance, and behavior of Atlantic bluefin tuna and the Northern right whale in relation to their environment and prey. We used integrated data from NOAA remote sensing and oceanographic databases. We also developed models of bluefin aggregation, leading to assessment of population size, and forecasting of distribution and abundance, and also for predicting the seasonal and spatial distribution of right whales from oceanographic precursors. Portions of this ecosystem-oriented GIS database were formatted for exchange and distribution via an interactive website (www.marinegis.org).

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Final Report

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Objective: The goals of this research program were to develop a GIS workstation to examine the distribution, relative abundance, and behavior of the North Atlantic bluefin tuna (*Thunnus thynnus*) and the Northern Right Whale (*Eubalaena glacialis*) in relation to their environment and prey.

Approach: The bluefin tuna databases were comprised of multi-year, real time spatial and temporal information on shoals and individual movements. Right whale databases were examined to identify movement modes and interaction with oceanographic features. We hoped to provide an ecosystem-based portrayal of these top predators in the Gulf of Maine and the northwest Atlantic.

Once the GIS and spatial analysis system architecture was in place, we established integrated data layers on oceanographic and environmental conditions from NOAA satellite remote sensing sources (AVHRR), USGS bathymetric data, the Distributed Oceanographic Data (DODS) system (frontal analysis). More traditional databases on prey location and abundance were examined when available. In addition, a spatially explicit individual based model (SIBM) and population models were developed to examine how multiple factors affect the measurement bias and estimation uncertainty of population abundance and distribution. As part of this effort, an automated digital image analysis system (SAIA) was constructed for analysis of bluefin schools from aerial photographs.

Our long-range goals were to (1) create the capability to build models on aggregation behavior of bluefin tuna and their prey, leading to direct assessment of population size, and forecasting their distribution and abundance and (2) develop a model for predicting the seasonal and spatial distribution of right whales from oceanographic precursors. Portions of this ecosystem-oriented GIS database on bluefin tuna and right whales were formatted for exchange and distribution via an interactive website (www.marinegis.org). Several of the manuscripts and publications resulting from this research (that are completed) are included as appendices, and graduate student Newlands, who's work was supported by this grant, has submitted his dissertation draft for review.

During the initial stages of this grant we were focused on building an analytical GIS system that could be used to examine the distribution and movements of bluefin tuna and right whales in the Gulf of Maine and beyond. Initially, we placed all of the species, cartographic and political data in our GIS and formatted them into a common projection. The species data included aerial surveys, line transect surveys, short term radio and sonic tagging, and long term pop-up archival satellite tagging. Background, cartographic and political data included state boundaries, bathymetric data, shipping lanes, fisheries closure areas, and marine sanctuaries.

After the initial data were processed, we conducted a thorough search of the available environmental datasets and biological prey databases. We used sea surface temperature data (SST) and derived products because these overlapped continuously with the bluefin tuna and right whale datasets. While we were interested in incorporating ocean color data, the timelines of both of these datasets start after 1993 (end of CZCS operation) and before fall of 1997 (launch of SeaWiFS). The SST database includes raw SST temperature data, and temperature gradient data. These gradient data, or SST fronts, serve as one of the primary interactions studied during this grant period. We also explored Sea Surface Height (SSH) data from the TOPEX/Poseidon satellites, with preliminary analysis and plotting of popup archival data from bluefin tuna migration paths. This yielded promising results, and as location estimation algorithms continues to develop for these tags, this dataset will be helpful in identifying the dynamics of migration. However, current SSH data are more global in coverage, and do not have great resolution or application in relatively shallow areas like the Gulf of Maine. Thus we haven't fully incorporated these data into our analysis.

For the biological prey data, our options were more limited. The only prey datasets relevant to this study were collected by the Northeast Fisheries Science Center (NMFS, Woods Hole, MA). The NEFSC conducts bi-annual ground fish trawl surveys in the GOM and adjacent areas. NEFSC conducted surveys concurrent with two years of our bluefin surveys (1994 & 1995). While these surveys detected some of the prey items of bluefin, they were completed early in the bluefin season (July), and were point trawls with limited spatial resolution. Consequently, they had limited value for the present analysis. For right whales, the best spatial-temporal match of datasets is the MARMAP copepod database, but the data for the 1996-1997 seasons have not been analyzed and made available. In addition, the spatial and temporal resolution is too large for the type of analyses that we've conducted. One modeled data layer that would be of interest is the individual based model of copepod distribution developed at Dartmouth's Numerical Methods Laboratory. No research group has attempted to transfer these data to a GIS, but it might be a productive dataset to explore in the future.

To access SST fronts for the Gulf of Maine we turned to the Distributed Oceanographic Data System (DODS). Peter Cornillon's lab at the University of Rhode Island developed DODS as a way to share oceanographic data between investigators. DODS stores data online in a variety of servers and requires a series of clients to access the various data sets. While an ArcInfo client is currently under development, as of now Matlab, IDL, MS-Excel, and a number of shareware applications are the only DODS compatible clients. Thus we purchased a Linux computer and installed both Matlab and the DODS client application for Matlab. With some experimentation we were able to successfully access both SST data and SST front data for use in the environmental database. This process has been detailed in a poster presented last year by Schick. It requires a series of Matlab programs to query and format the data. To generate new coverages or datalayers in ArcInfo, the data must be formatted in a specific manner. This formatting was done in Matlab. The data are pulled off the DODS servers and stored locally as ASCII text files. Then the coverages can be generated in ArcInfo. However, since there are upwards of four AVHRR images for each day, there are an immense amount of text files. Thus we wrote a series of Arc Macro Language scripts, or AML's, to loop through the formatted ASCII files and generate coverages as well as interpolated grids. For example, for each day, we would generate an AVHRR raster image of SST, a vector coverage of all the fronts seen in that image, a raster image of the distance to the nearest front, and raster image of the density of fronts seen in a specified time window (to generate a picture of frontal persistence). These scripts enabled an immense amount of data to be processed, which preserved the naming scheme from DODS. The poster detailing this transfer, along with the perl and AML scripts are available as part of a web tutorial explaining this process: see url: www.marinegis.org/fronts.html

Once the environmental data were created, values for each of the variables were extracted for statistical analysis. Additional automation using AML was used to parse through the species data on a daily basis, and extract the time and region specific environmental values. The output from this AML was pasted together in Excel. The last step in the technical phase of the analysis was to run the datasets through a variety of statistical tests, including simple and partial Mantel tests, logistic regression, and Classification and Regression Tree (CART) analysis. All of these statistical tests were performed using S-Plus. The results were collated, inspected, and then plotted.

Accomplishments: This work combining GIS, spatial statistics and modeling methods has led to a large body of work found in the publications and manuscripts submitted for publication in the peer-reviewed scientific literature. The application of GIS and spatial statistics showed that right whales move around the ocean in ways that may be predictable relative to oceanographic features. The bluefin tuna work has identified a number of ways in which tuna relate to the marine environment that could enhance the understanding of migration and distribution patterns, spawning and social biology, and population assessment. Modeling exercises undertaken as part of this work have evaluated the three dimensional aspects of tuna schools, the movements of individuals as a method for estimating schooling behavior and occurrence, and the potential for counting tuna with corrections for schooling, movement, and vertical behavior. The manuscripts are listed below and attached as appendices.

In addition, the contract called for the development of a website with information about our activities, links to other relevant marine and GIS sites, and charts of right whale and tuna distributions, as well as pdf files of selected manuscripts. The website url is http://www.marinegis.org The website includes maps of our study area, tutorials on DODS and ArcInfo, lists of papers we have published, highlights of related research on turtle tracking and SPUE-GIS work conducted in our lab. After our papers on bluefin tuna and right whales are accepted for publication, pdf copies of the manuscripts will be made available. In addition, we have made several animations of the distributions of right whales and bluefin tuna in relation to SST fronts, which will be made available after publication.

Conclusions: The results of this work demonstrate that the application of GIS and spatial statistical methods to wildlife studies has tremendous promise in the marine environment. It also demonstrates that the extension of these habitat studies through modeling could lead to better assessments of population size, as well as a better understanding of multiple features of the interactions between fish, whales, and the oceanography of an area. Although there were limitations to the datasets studied, additional data on ocean color, prey fields, and currents are becoming readily available, and could be included in these types of analyses. However, this project consisted of a large number of non-trivial details, in particular, the issue of acquiring and matching geo-referenced, calibrated, and appropriately formatted datasets. In many cases, datasets had to be converted from one format to another, or from one geographical projection to another, in order to create accurately matched layers for analysis. These tasks were time-consuming and required advanced GIS, mathematical, and statistical skills.

Significance: The analyses presented here show significant advances in the ability of biologists to use oceanographic features as a method for predicting animal movements and distributions. Continued work of this type could focus on identifying those oceanographic features that predict most of the variability in an animal's movements or distribution patterns. Such ocean features, if available from remotely sensed satellite imagery, would be especially useful for managers attempting to manage fisheries or reduce conflicts between wildlife and human activities.

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Publications or Manuscripts completed under ONR Grant #N00014-98-1-0852

1.) Kraus, S.D., R.S. Schick, and C.K. Slay. The feasibility of linking North Atlantic right whale movements with oceanography.

2.) Schick, R. S., Goldstein, J. and Lutcavage, M.E. In review. Bluefin tuna (*Thunnus thynnus*) distribution in relation to sea surface temperature fronts in the Gulf of Maine (1994-1996).

3.) Newlands, N. 2002. Research Report (for ONR): Shoaling dynamics and abundance estimation: Atlantic bluefin tuna (*Thunnus thynnus*). Dissertation Summary , Univ. of British Columbia, Vancouver, BC Canada

4.) Newlands, N. and M.L. Lutcavage. 2001. From Individuals to Local Population Densities: Movements of North Atlantic Bluefin Tuna (*Thunnus thynnus*) in the Gulf of Maine/ Northwestern Atlantic. *In* Electronic Tagging and Tracking of Marine Fisheries, J.R. Sibert and J.L. Nielsen (eds). Kluwer Academic, Netherlands. pgs. 421-441.

5.) Schick, R.S. 2002. Using GIS to Track Right Whales and Bluefin Tuna in the Atlantic Ocean. In Undersea with GIS, D.J. Wright (ed.), ESRI Press Redlands, CA.

6.) Schick, R.S. 2001. Tuna distribution in relation to physical features in the Gulf of Maine. *In*: Conservation Geography: Case Studies in GIS, Computer Mapping, and Activism, C. Convis (ed.), ESRI Press Redlands, CA.

7.) Schick, R.S. 2002. Using GIS to Track Right Whales and Bluefin Tuna in the Atlantic Ocean - an update. *in press*, ESRI Press Redlands, CA.

Appendices

GIS-related Presentations

Schick, R.S. Using ArcInfo, Perl, and the Distributed Oceanographic Data System (DODS) to analyze movements of right whales in relation to sea surface temperature fronts. The Use of Geomatic Technologies for Marine Mammal Scientists II at the Fourteenth Biennial Conference on the Biology of Marine Mammals. November 28, 2001. Vancouver, BC.),

M. Lutcavage. Occurrence and Lifestyles of Bluefin Tuna in the Gulf of Maine. Fisheries, Oceanography and Society, Marine Protected Areas: Design and Implementation for Conservation and Fisheries Restoration. Ocean Life Institute, Woods Hole Oceanographic Institution, MA, Aug, 2001.

Newlands, N. and M. Lutcavage. 2000. Integrating cross-scale movement information from tagging and tracking studies of North Atlantic bluefin tuna (*Thunnus thynnus*).Symposium on Tagging and Tracking Marine Fish With Electronic Devices. Un. of Hawaii, East-West Center, Honolulu HI, Feb 7-11, 2000.

Brill, R.W., Lutcavage, M.E., Schick, R.S. Schick, and N.K. Newlands. Environmental Influences on Movements and Depth Distributions of Tunas and Billfishes. Presented at the New Insights Into the Ecology of Pelagic Animals From Applications of Electronic Tags, during the 2002 Ocean Sciences Meeting. February 11th 15th, 2002. Honolulu, HI.

Papers 1-7 listed above

Note: We expect that 5 additional manuscripts will be prepared for publication in 2002 from Newlands' dissertation.